

Project Update: A New Foundation of Attack Trees in Linear Logic

Harley Eades III

Computer Science
Augusta University
harley.eades@gmail.com

Abstract. In this short paper I provide an update on the status of newly funded research project investigating founding attack trees in the resource conscious theory called linear logic.

1 Introduction

What is a mathematical model of attack trees? There have been numerous proposed answers to this question. Some examples are propositional logic, multisets, directed acyclic graphs, source sink graphs (or parallel-series pomsets), Petri nets, and Markov processes. Is there a unifying foundation in common to each of these proposed models? Furthermore, can this unifying foundation be used to further the field of attack trees and build new tools for conducting threat analysis?

The answer to the first question is positive, but the answer to the second question is open. Each of the proposed models listed above have something in common. They can all be modeled in some form of a symmetric monoidal category¹ [7,1,2,3] – for the definition of a symmetric monoidal category see Appendix A. That is all well and good, but what can we gain from monoidal categories?

Monoidal categories are a mathematical model of linear logic as observed through the beautiful Curry-Howard-Lambek correspondence [6]. In linear logic every hypothesis must be used exactly once, and hence, if we view a hypothesis as a resource, then this property can be stated as every resource must be consumed. This linearity property is achieved by removing the structural rules for weakening and contraction from classical or intuitionistic logic. Thus, from a resource perspective, resources cannot be spontaneously created or duplicated – hence, propositional logic can be viewed as a degenerate, from a resource perspective, form of linear logic.

Multisets and Petri nets both capture the idea that the nodes of an attack tree capture both the attack action and the state – the resource – of the system being analyzed. As it turns out, linear logic has been shown to be a logical foundation for multisets [7] and Petri Nets [1]. Thus, linear logic has the ability

¹ I provide a proof that the category of source sink graphs is monoidal in Appendix B.

to model the state as well as attack actions of the goals of an attack tree. We propose that linear logic be used as the logical foundation of attack trees.

This project's² main goal is to determine the suitability of linear logic as a foundation for attack trees. The type of attack trees we consider in this paper are attack trees with sequential composition similar to Jhawar et al. [5]. Attack trees consist of two layers: the logical layer or process tree, and the quantitative layer. One interesting aspect of our proposed foundation is that the logical layer can come to the aid of the quantitative layer.

At the logical layer the base attacks of an attack tree will correspond to atomic formulas in linear logic, and each branching node of an attack tree will correspond to a binary operator in linear logic. Adding costs corresponds to annotating the atomic formulas with some base cost, and then annotating the binary operators with a cost computed from the costs of their respective left operand (left subtree) and right operand (right subtree). The most interesting aspect of adding costs is that computing the costs at the branching nodes is done during the construction of a derivation using the inference rules of the logic.

The inference rules of linear logic provide a number of benefits when constructing attack trees. First, the inference rules will certify that an attack tree is constructed correctly and all costs on branching nodes will be computed from the costs of the left and right subtrees. On top of that the inference rules offer a means of proving when two attack trees are equivalent. Leveraging the fact that language of attack trees corresponds to a very simple fragment of linear logic, e.g. linear implication is not needed, I conjecture that proving equivalence of attack trees can be automated. Thus, this could be used in practice to certify the correctness of transformations of attack trees maintaining the resource based semantics.

2 A Short Introduction to Ordered Linear Logic

Before defining attack trees and the logical theory behind them we first give a brief introduction to linear logic to aid the readers understanding. Linear logic is due to the work of Girard [4], and has since seen many applications in computer science, natural languages, mathematics, and philosophy.

We call a logical formula **linear** if and only if all of its hypotheses are used exactly once. Linear logic is then characterized by the logic of linear formulas. It can come in various flavors: intuitionistic, classical, modal, etc. Furthermore, it can come in several different formulations: natural deduction, sequent calculus, axiomatic, etc. Every logic in this paper will be intuitionistic and in natural deduction form.

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3 Attack Trees

In this section I introduce attack trees with sequential composition first proposed by Jhawar et al. [5]. One of the projects ultimate goals is to extend attack trees with even more operators driven by our choice of semantics, but I leave this to future work.

The definition of attack trees is broken up into two parts. First, the definition of pre-attack trees.

Definition 1. Suppose \mathbf{B} is a set of base attack, \mathbf{C} is a set of costs, $\Sigma = \{\text{op}_\odot, \text{op}_\triangleright, \text{op}_\sqcup\}$ is a set of binary operations on \mathbf{C} , and $I = \{i_\odot, i_\triangleright, i_\sqcup\}$ is a set of identities, such that, each $l \in \{\text{op}_\odot, \text{op}_\sqcup\}$, $\text{op}_l \in \Sigma$ and $i_l \in I$ make $(\mathbf{C}, \text{op}_l, i_l)$ a commutative monoid, and $(\mathbf{C}, \text{op}_\triangleright, i_\triangleright)$ a monoid.

The following defines the syntax of **Pre-attack Trees** given an assignment $\eta : \mathbf{B} \rightarrow \mathbf{C}$ of base attacks to costs:

$$T ::= (b, \eta(b)) \mid T_1 \odot_{\text{op}_\odot} T_2 \mid T_1 \sqcup_{\text{op}_\sqcup} T_2 \mid T_1 \triangleright_{\text{op}_\triangleright} T_2$$

I denote unsynchronized parallel composition of attacks by $T_1 \sqcup_{\text{op}_\sqcup} T_2$, choice between attacks by $T_1 \odot_{\text{op}_\odot} T_2$, and sequential composition of attacks by $T_1 \triangleright_{\text{op}_\triangleright} T_2$.

The most interesting aspect of the previous definition is that each branching operator is annotated with an monoidal operation that computes the cost at that branch. Thus, given a preattack trees we do not know the cost of the root node.

I characterize valid attack trees as preattack trees in which the given branching operators are used to construct the costs of the tree. This notion of validity is captured by the inference rules given in Figure 1. The valid attack tree infer-

$$\begin{array}{c} \frac{}{\cdot; (b, c) \vdash_c b} \text{ T_VAR} \qquad \frac{}{(b, c); \cdot \vdash_c b} \text{ T_VARC} \\[10pt] \frac{\Gamma_1; \Delta_1 \vdash_{c_1} T_1 \quad \Gamma_2; \Delta_2 \vdash_{c_2} T_2}{\Gamma_1, \Gamma_2; \Delta_1, \Delta_2 \vdash_{\text{op}_\odot(c_1, c_2)} T_1 \odot_{\text{op}_\odot} T_2} \text{ T_PARA} \\[10pt] \frac{\Gamma_1; \Delta_1 \vdash_{c_1} T_1 \quad \Gamma_2; \Delta_2 \vdash_{c_2} T_2}{\Gamma_1, \Gamma_2; \Delta_1, \Delta_2 \vdash_{\text{op}_\triangleright(c_1, c_2)} T_1 \triangleright_{\text{op}_\triangleright} T_2} \text{ T_SEQ} \end{array}$$

Fig. 1. Inference Rules for Valid Attack Trees

ence rules constitute a very simple linear logic which guarantees that each base attack is used exactly once, and the cost of every subtree is calculated correctly. We have now arrived at the following definition.

Definition 2. Suppose Γ is a sequence of pairs of base attacks and their costs that are to be used as leafs to the parallel branching operator, and Δ is a sequence of pairs of base attacks and their costs that are to be used as leafs to the sequential branching operator. A preattack tree, T , is an **attack tree** if and only if $\Gamma; \Delta \vdash_c T$ is derivable using the valid attack tree inference rules.

4 A Linear Logic for Attack Trees

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Appendix

A Symmetric Monoidal Categories

This appendix provides the definitions of both categories in general, and, in particular, symmetric monoidal closed categories. We begin with the definition of a category:

Definition 3. A *category*, \mathcal{C} , consists of the following data:

- A set of objects \mathcal{C}_0 , each denoted by A, B, C , etc.
- A set of morphisms \mathcal{C}_1 , each denoted by f, g, h , etc.
- Two functions **src**, the source of a morphism, and **tar**, the target of a morphism, from morphisms to objects. If **src**(f) = A and **tar**(f) = B , then we write $f : A \rightarrow B$.

- Given two morphisms $f : A \rightarrow B$ and $g : B \rightarrow C$, then the morphism $f;g : A \rightarrow C$, called the composition of f and g , must exist.
- For every object $A \in \mathcal{C}_0$, there must exist a morphism $\text{id}_A : A \rightarrow A$ called the identity morphism on A .
- The following axioms must hold:
 - (Identities) For any $f : A \rightarrow B$, $f; \text{id}_B = f = \text{id}_A; f$.
 - (Associativity) For any $f : A \rightarrow B$, $g : B \rightarrow C$, and $h : C \rightarrow D$, $(f;g);h = f;(g;h)$.

Categories are by definition very abstract, and it is due to this that makes them so applicable. The usual example of a category is the category whose objects are all sets, and whose morphisms are set-theoretic functions. Clearly, composition and identities exist, and satisfy the axioms of a category. A second example is preordered sets, (A, \leq) , where the objects are elements of A and a morphism $f : a \rightarrow b$ for elements $a, b \in A$ exists iff $a \leq b$. Reflexivity yields identities, and transitivity yields composition.

Symmetric monoidal categories pair categories with a commutative monoid like structure called the tensor product.

Definition 4. A *symmetric monoidal category (SMC)* is a category, \mathcal{M} , with the following data:

- An object I of \mathcal{M} ,
- A bi-functor $\otimes : \mathcal{M} \times \mathcal{M} \rightarrow \mathcal{M}$,
- The following natural isomorphisms:

$$\begin{aligned}\lambda_A &: I \otimes A \rightarrow A \\ \rho_A &: A \otimes I \rightarrow A \\ \alpha_{A,B,C} &: (A \otimes B) \otimes C \rightarrow A \otimes (B \otimes C)\end{aligned}$$

- A symmetry natural transformation:

$$\beta_{A,B} : A \otimes B \rightarrow B \otimes A$$

– Subject to the following coherence diagrams:

$$\begin{array}{ccc}
((A \otimes B) \otimes C) \otimes D & \xrightarrow{\alpha_{A,B,C} \otimes \text{id}_D} & (A \otimes (B \otimes C)) \otimes D \\
\downarrow \alpha_{A \otimes B, C, D} & & \downarrow \alpha_{A, B \otimes C, D} \\
(A \otimes B) \otimes (C \otimes D) & & A \otimes ((B \otimes C) \otimes D) \\
\downarrow \alpha_{A, B, C \otimes D} & \xleftarrow{\text{id}_A \otimes \alpha_{B, C, D}} & \downarrow \\
A \otimes (B \otimes (C \otimes D)) & & A \otimes ((B \otimes C) \otimes D) \\
\downarrow \alpha_{A, B, C} & \xrightarrow{\beta_{A, B} \otimes \text{id}_C} & \downarrow \alpha_{B, A, C} \\
(A \otimes B) \otimes C & & (B \otimes A) \otimes C \\
\downarrow \alpha_{A, B, C} & & \downarrow \alpha_{B, A, C} \\
A \otimes (B \otimes C) & & B \otimes (A \otimes C) \\
\downarrow \beta_{A, B \otimes C} & & \downarrow \text{id}_B \otimes \beta_{A, C} \\
(B \otimes C) \otimes A & \xrightarrow{\alpha_{B, C, A}} & B \otimes (C \otimes A)
\end{array}$$

$$\begin{array}{ccc}
(A \otimes I) \otimes B & \xrightarrow{\alpha_{A, I, B}} & A \otimes (I \otimes B) \\
\searrow \rho_A & & \swarrow \lambda_B \\
& A \otimes B & \\
\end{array}
\qquad
\begin{array}{ccc}
A \otimes B & & \\
\swarrow \beta_{A, B} & \searrow \text{id}_{A \otimes B} & \\
B \otimes A & \xrightarrow{\beta_{B, A}} & A \otimes B
\end{array}$$

$$\begin{array}{ccc}
I \otimes A & \xrightarrow{\beta_{I, A}} & A \otimes I \\
\searrow \lambda_A & & \swarrow \rho_A \\
& A &
\end{array}$$

Monoidal categories posses additional structure, and hence, ordinary functors are not enough, thus, the notion must also be extended.

Definition 5. Suppose we are given two monoidal categories $(\mathcal{M}_1, \top_1, \otimes_1, \alpha_1, \lambda_1, \rho_1)$ and $(\mathcal{M}_2, \top_2, \otimes_2, \alpha_2, \lambda_2, \rho_2)$. Then a **monoidal functor** is a functor $F : \mathcal{M}_1 \rightarrow \mathcal{M}_2$, a map $m_{\top_1} : \top_2 \rightarrow F\top_1$ and a natural transformation $m_{A, B} : FA \otimes_2 FB \rightarrow F(A \otimes_1$

B) subject to the following coherence conditions:

$$\begin{array}{ccc}
(FA \otimes_2 FB) \otimes_2 FC & \xrightarrow{\alpha_{2FA, FB, FC}} & FA \otimes_2 (FB \otimes_2 FC) \\
\downarrow m_{A,B} \otimes \text{id}_{FC} & & \downarrow \text{id}_{FA} \otimes m_{B,C} \\
F(A \otimes_1 B) \otimes_2 FC & & FA \otimes_2 F(B \otimes_1 C) \\
\downarrow m_{A \otimes_1 B, C} & & \downarrow m_{A, B \otimes_1 C} \\
F((A \otimes_1 B) \otimes_1 C) & \xrightarrow{F\alpha_{1A, B, C}} & F(A \otimes_1 (B \otimes_1 C))
\end{array}$$

$$\begin{array}{ccc}
\top_2 \otimes_2 FA & \xrightarrow{\lambda_{2FA}} & FA \\
\downarrow m_{\top_1} \otimes \text{id}_{FA} & & \uparrow F\lambda_{1A} \\
F\top_1 \otimes_2 FA & \xrightarrow{m_{\top_1, A}} & F(\top_1 \otimes_1 A)
\end{array}
\quad
\begin{array}{ccc}
FA \otimes_2 \top_2 & \xrightarrow{\rho_{2FA}} & FA \\
\downarrow \text{id}_{FA} \otimes m_{\top_1} & & \uparrow F\rho_{1A} \\
FA \otimes_2 F\top_1 & \xrightarrow{m_{A, \top_1}} & F(A \otimes_1 \top_1)
\end{array}$$

B Source Sink Graphs are Symmetric Monoidal

In this appendix I show that the category of source-sink graphs defined by Jhawar et al. [5] is symmetric monoidal. First, recall the definition of source-sink graphs and their homomorphisms.

Definition 6. A **source-sink graph** over B is a tuple $G = (V, E, s, z)$, where V is the set of vertices, E is a multiset of labeled edges with support $E^* \subseteq V \times B \times V$, $s \in V$ is the unique start, $z \in V$ is the unique sink, and $s \neq z$.

Suppose $G = (V, E, s, z)$ and $G' = (V', E', s', z')$. Then a **morphism between source-sink graphs**, $f : G \rightarrow G'$, is a graph homomorphism such that $f(s) = s'$ and $f(z) = z'$.

Suppose $G = (V, E, s, z)$ and $G' = (V', E', s', z')$ are two source-sink graphs. Then given the above definition it is possible to define sequential and non-communicating parallel composition of source-sink graphs where I denote disjoint union of sets by $+$ (p 7. [5]):

Sequential Composition :

$$G \triangleright G' = ((V \setminus \{z\}) + V', E^{[s'/z]} + E', s, z')$$

Parallel Composition :

$$G \odot G' = ((V \setminus \{s, z\}) + V', E^{[s'/s, z'/z]} + E', s', z')$$

It is easy to see that we can define a category of source-sink graphs and their homomorphisms. Furthermore, it is a symmetric monoidal category where parallel composition is the symmetric tensor product. It is well-known that any

category with co-products is symmetric monoidal where the co-product is the tensor product.

I show here that parallel composition defines a co-product. This requires the definition of the following morphisms:

$$\begin{aligned} \text{inj}_1 &: G_1 \rightarrow G_1 \odot G_2 \\ \text{inj}_2 &: G_2 \rightarrow G_1 \odot G_2 \\ \langle f, g \rangle &: G_1 \odot G_2 \rightarrow G \end{aligned}$$

In the above $f : G_1 \rightarrow G$ and $g : G_2 \rightarrow G$ are two source-sink graph homomorphisms. Furthermore, the following diagram must commute:

$$\begin{array}{ccccc} & & G & & \\ & f \swarrow & \uparrow \langle f, g \rangle & \searrow g & \\ G_1 & \xrightarrow{\text{inj}_1} & G_1 \odot G_2 & \xleftarrow{\text{inj}_2} & G_2 \end{array}$$

Suppose $G_1 = (V_1, E_1, s_1, z_1)$, $G_2 = (V_2, E_2, s_2, z_2)$, and $G = (V, E, s, z)$ are source-sink graphs, and $f : G_1 \rightarrow G$ and $g : G_2 \rightarrow G$ are source-sink graph morphisms – note that $f(s_1) = g(s_2) = s$ and $f(z_1) = g(z_2) = z$ by definition. Then we define the required co-product morphisms as follows:

$$\begin{aligned} \text{inj}_1 &: V_1 \rightarrow (V_1 \setminus \{s_1, z_1\}) + V_2 \\ \text{inj}_1(s_1) &= s_2 \\ \text{inj}_1(z_1) &= z_2 \\ \text{inj}_1(v) &= v, \text{ otherwise} \end{aligned}$$

$$\begin{aligned} \text{inj}_2 &: V_2 \rightarrow (V_1 \setminus \{s_1, z_1\}) + V_2 \\ \text{inj}_2(v) &= v \end{aligned}$$

$$\begin{aligned} \langle f, g \rangle &: (V_1 \setminus \{s_1, z_1\}) + V_2 \rightarrow V \\ \langle f, g \rangle(v) &= f(v), \text{ where } v \in V_1 \\ \langle f, g \rangle(v) &= g(v), \text{ where } v \in V_2 \end{aligned}$$

It is easy to see that these define graph homomorphisms. All that is left to show is that the diagram from above commutes:

$$\begin{aligned} (\text{inj}_1; \langle f, g \rangle)(s_1) &= \langle f, g \rangle(\text{inj}_1(s_1)) \\ &= g(s_2) \\ &= s \\ &= f(s_1) \\ (\text{inj}_1; \langle f, g \rangle)(z_1) &= \langle f, g \rangle(\text{inj}_1(z_1)) \\ &= g(z_2) \\ &= z \\ &= f(z_1) \end{aligned}$$

Now for any $v \in V_1$ we have the following:

$$\begin{aligned}(\text{inj}_1; \langle f, g \rangle)(v) &= \langle f, g \rangle(\text{inj}_1(v)) \\ &= f(v)\end{aligned}$$

The equation for inj_2 is trivial, because inj_2 is the identity.